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EVALUATION OF CONDITIONING AND DEWATERING SEWAGE SLUDGE BY FREEZING

Milwaukee Sewerage Commission, Wisconsin

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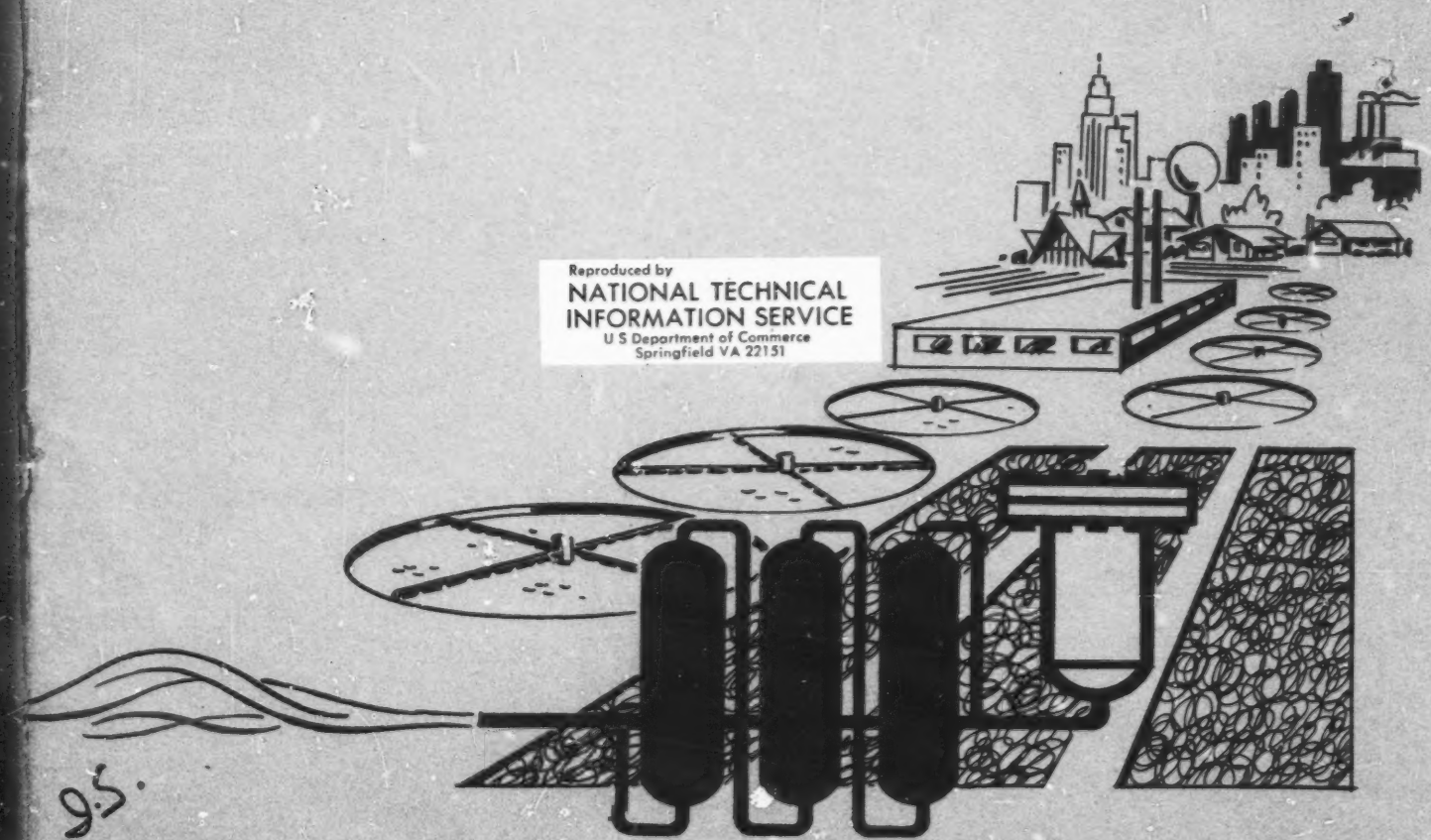

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EVALUATION OF CONDITIONING

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by

Sewerage Commission of the City of Milwaukee
Milwaukee, Wisconsin 53201

for the

ENVIRONMENTAL PROTECTION AGENCY

Program #11010 EVE
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This report has been reviewed by the Water Quality Office, EPA, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

It is evident that research into new sludge handling processes has great potential for increasing the efficiency and decreasing the cost of sludge handling and disposal. Of special interest, is the investigation of methods which significantly reduce secondary treatment sludge volumes for subsequent treatment and disposal. This project was initiated to investigate, develop, and evaluate a prototype system for the conditioning and dewatering of waste activated sludge by freezing. The activated sludge used was that from the treatment plant of the Sewerage Commission of the City of Milwaukee, Milwaukee, Wisconsin.

The project work scope was divided into two phases: (1) the laboratory investigation phase and (2) the engineering design and evaluation phase. The purpose of the laboratory investigation phase was to obtain the basic process and design parameters for a freeze conditioning system. Emerging from the laboratory investigation and carried forward to the engineering design phase was a freeze-conditioning system consisting of the following process elements: (1) Flotation thickening prior to freezing, (2) Freezing in thin sheets, (3) Thawing of the frozen product, and (4) Dewatering of the thawed sludge. The objective of the engineering design phase was the development of a freeze-conditioning system to handle three tons dry solids per day of activated sludge.

It was concluded that the freeze conditioning concept, from a technical standpoint, has definite merit as a sludge conditioning process. However, an evaluation of the freeze conditioning process and comparison with the existing chemical conditioning method presently employed showed that the equipment capital costs, operating costs, and space requirements were appreciably greater for the freeze conditioning process than for the existing chemical conditioning method. Attempts to reduce freeze-conditioning operating costs by reducing the refrigeration work required were found to be technically feasible, but would result in appreciably increasing the equipment capital costs above that for the freeze conditioning system presently envisioned, thereby aggravating an unsatisfactory situation.

It was recommended that the objectives of the project be redirected to the investigation of alternate sludge conditioning and sludge dewatering means.

This report was submitted in fulfillment of Grant No. WPRD 71-01-68, Program No. 11010 EVE, between the Federal Water Quality Administration and the Sewerage Commission of the City of Milwaukee, Wisconsin.

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SECTION I

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the work done on the subject grant project:

1. The freeze-conditioning concept, from the standpoint of technical process efficiency, has definite merit as a means of conditioning waste activated sludge for subsequent dewatering.

2. Engineering evaluation of the freeze-conditioning process and comparison with the conventional chemical ($FeCl_3$) conditioning method presently employed showed that the equipment capital costs, operating costs and space requirements were appreciably higher for the freeze method than for the chemical method.

3. Attempts to reduce freeze-conditioning operating costs by reducing the refrigeration work required were found to be technically feasible, but would result in appreciably increasing the equipment capital costs and space requirements above those for the freeze system presently envisioned, thereby aggravating an already unsatisfactory economic situation.

On the basis of these conclusions, it was recommended that the objectives of the project be redirected to the investigation of alternate sludge conditioning and dewatering means.

SECTION II

INTRODUCTION

Residual sludges are by-products arising from the treatment of wastewaters and contain, in more concentrated form, the objectionable pollutants removed in the wastewater treatment process. Although the volume of residual sludges obtained is relatively small, usually 2% to 3% of the wastewater volume treated, sludge handling and disposal is complex, troublesome, and represents up to 25% to 50% of the capital and operating costs of a waste treatment plant (1). Moreover, the problem is growing. With the expansion of the economy and the population and with the greater degree of treatment required, it is expected, within the next 10 to 15 years, that the volume of sludge requiring handling and disposal will increase by 60% to 70% (2). By far, the major portion of the increased sludge volume expected will be obtained from secondary treatment sludges, which are less concentrated than primary sludges, and which are most difficult and expensive to treat. For example, in 1980 it is anticipated that 140 million gallons per day of secondary sludge (2% solids) will be produced, whereas only about 10 million gallons per day of primary sludge (6% solids) are expected in that year (2).

Sludge handling for ultimate disposal consists of a series of dewatering steps in which the volume of sludge is progressively reduced by removal of the water associated with the sludge solids. The process steps usually associated with sludge handling and disposal include the following:

1. Thickening
    a. Sedimentation
    b. Flotation
2. Digestion
    a. Aerobic
    b. Anaerobic
3. Dewatering
    a. Sand beds
    b. Lagoons

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c. Vacuum Filtration

d. Centrifugation

4. Ultimate Disposal

a. Landfill

b. Discharge to sea

c. Drying for soil conditioning

d. Oxidation

(1) Incineration

(2) Wet oxidation

(3) Atomized suspension technique

For a particular location, the combination of the sludge handling and disposal steps to be used are integrated in such a manner as to arrive at an optimum economical solution. Wherever possible, advantage is taken of new developments by incorporating them into the process scheme.

It is apparent from the above brief discussion that research into sludge handling has potential value for increasing process efficiency and decreasing the cost of the total waste treatment process. It is further evident that the greatest benefit which may be derived from sludge handling research lies in the investigation of means for efficiently and economically handling secondary treatment sludge volumes for subsequent treatment and disposal.

Recently, attention and emphasis has been placed upon physical methods for conditioning sludges to enhance dewatering and disposal without the aid of chemicals (3). Freezing of sludge and subsequent thawing is a physical method which shows promise as a sludge conditioning means (4). Freezing of activated sludge causes the suspended solids to agglomerate and form relatively large floc particles. Upon thawing, the separation and compaction properties of the solids suspension are significantly improved over those observed before freezing. Furthermore, dewatering of sludge is appreciably enhanced by the freeze conditioning process. For example, dewatering of freeze conditioned activated sludge using gravity drain on screens varying in size from 24 to 40 U.S. mesh has been reported (5). The mass loadings used during the dewatering of the freeze conditioned activated sludge was on the order of 60

pounds per hour of dry solids per square foot as compared to 1 to 5 pounds per hour per square foot for conventional vacuum filtration.

The applicability of utilizing the freezing process for conditioning waste activated sludge was demonstrated to the City of Milwaukee by the Technical Center of Rex Chainbelt Inc. and the results of the studies performed (5) served as a basis for the grant obtained (WPRD 71-01-68) to conduct a program for demonstrating, on a relatively large scale, this dewatering technique. The grant was obtained by the Milwaukee Sewerage Commission, Milwaukee, Wisconsin from the Federal Water Pollution Control Administration. The work performed under this grant was done by the Technical Center, Rex Chainbelt Inc., Milwaukee, Wisconsin under contract to the Milwaukee Sewerage Commission.

The waste activated sludge handling and disposal facilities of the Milwaukee Sewerage Commission's Water Pollution Control Plant include (1) gravity thickening, (2) chemical conditioning, (3) vacuum filtration, and (4) heat drying. The dried sludge is marketed as the fertilizer, Milorganite. The Commission uses ferric chloride to condition its waste activated sludge, and the annual chemical cost is about $750,000, based on a dose level of about 250 lb $FeCl_3$ per dry ton of solids.

The purpose of the investigation conducted under this grant was to evaluate the freeze conditioning and dewatering technique on a scale large enough to obtain meaningful data for direct comparison with the conditioning and dewatering methods presently employed at Milwaukee.

SECTION III

GRANT OBJECTIVES

The objectives of the project conducted under this grant were as follows:

1. To evaluate the effect of freeze conditioning of waste activated sludge at the Milwaukee Sewerage Commission Water Pollution Control Plant on solids dewatering characteristics. It was felt that the freeze conditioning technique, which beneficially alters the characteristics of the sludge, offers a new and promising method for solids dewatering.

2. To reduce or eliminate the need for chemical sludge conditioners in the vacuum filtration dewatering process. At the present time, the Milwaukee Sewerage Commission spends about $750,000 each year for chemicals to condition sludge prior to vacuum filtration. If, through the freeze conditioning technique, the need for chemicals could be eliminated or reduced, operational costs for sludge dewatering could be reduced.

3. To investigate and evaluate new techniques for sludge dewatering through the design and demonstration of a continuous gravity screen filter. In addition, modifications of a conventional vacuum filter would be made to evaluate the feasibility of using conventional dewatering equipment for handling freeze conditioned sludge. For example, at Milwaukee, modifications of existing conventional vacuum filters to handle the anticipated increased solids dewatering loadings from freeze conditioning would minimize the future need for additional conventional vacuum filtration equipment.

4. To study and evaluate the physical and chemical changes that occur as a result of freeze conditioning and dewatering and to relate these changes to the fertilizer properties and characteristics of the dried sludge.

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SECTION IV

WORK SCOPE AND PLAN OF OPERATION

It was originally proposed that the objectives of the project be met through performance of a work scope encompassing two phases over a period of two years. The following discussion of the work scope and plan of operation identifies each of these phases, outlines the scope of each one, and defines their interrelationships with respect to the proposed total effort. The primary thrust of this investigation was to be directed to the development and evaluation of a three ton dry solids per day demonstration system for conditioning and dewatering waste activated sludge by freezing.

Phase I - Design, Fabrication and Evaluation of Batch Operation

Investigations of freezing rates and techniques and their related effect on the dewatering process were to be conducted. From the work performed by the Technical Center of Rex Chainbelt Inc. (5)(6), it was seen that freezing rates and techniques play an important role in the floc characteristics of the freeze conditioning process. Optimum freezing rates were to be determined to provide maximum utilization of the freezing system, consistent with favorable sludge conditioning. Moreover, methods of freezing were to be evaluated to provide the most effective heat transfer characteristics for a continuous system. The results of these investigations will have a significant bearing upon the design of the freezing and dewatering equipment to be used.

Following design, construction and installation of the system at the Milwaukee Jones Island plant, evaluation of batch freezing for sludge conditioning and dewatering of the conditioned sludge on a continuous prototype gravity filter was to be made. Operation of the freeze conditioning and dewatering system side by side with a conventional chemical conditioning and vacuum filter dewatering system would provide a means for evaluating the effectiveness of the freeze conditioning and dewatering technique. Operation of the freeze process with and without chemical aids would provide information as to the need for chemicals and to determine the interaction of variables which may occur as a result of chemical conditioners. The data obtained during operation would allow comparison of the two dewatering techniques from the standpoint of mass loadings, hydraulic loadings, cake and filtrate solids contents, and the physical and chemical properties of the filter cakes.

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After completion of the above evaluations, modifications to the conventional vacuum filter were to be made to allow the handling of freeze conditioned sludge on the vacuum filter. The modifications would include the design and fabrication of a feed system for depositing of sludge on the vacuum drum and substitution of a screen filter media in place of the conventional filter cloth. These modifications would be required because of the different floc characteristics of freeze conditioned sludge which would require a different feed system and filter media for maximum utilization of this conditioned sludge. Dewatering evaluations would be made on the modified vacuum filter to illustrate the potential increased operational efficiencies using freeze conditioned sludge. The data taken during this evaluation would allow direct comparison of conventional vacuum dewatering using chemical conditioners with that of vacuum dewatering of freeze conditioned sludge. Important information such as mass loadings, water throughput rates, solids concentration in the filtrate and filter cake and physical and chemical properties of the cake solids would then be available for direct comparison of the two dewatering techniques.

Phase II - Semi-Continuous System Operation and Evaluation

Using the results obtained in operation and evaluation of Phase I, a semi-continuous freezing and a continuous filtration using energy recovery methods with the prototype system were to be investigated. To optimize the freezing costs for sludge conditioning, careful recovery of the heat removed during freezing is required. The semi-continuous freezing and thawing system would use the heat removed during the freezing in one tank to thaw the frozen sludge in a second tank.

Evaluation of the dewatering process, using the sludge conditioned by the semi-continuous method outlined above, were to be demonstrated on the prototype gravity screen filter and the modified vacuum filter as described previously. Operational data obtained during these evaluations would enable comparison of the two dewatering techniques using freeze conditioned sludge as well as the evaluation of the semi-continuous freezing and dewatering system. Sufficient information which would allow the economic evaluation of the freeze conditioning process was also intended to be gathered during this phase.

SECTION V

DISCUSSION OF RESULTS

Actually, the above outlined plan of operation was not fully implemented. Only the laboratory investigations and a portion of the prototype engineering evaluation task in Phase I were completed. During the engineering design phase of the project, it became increasingly evident that the equipment capital costs and space requirements for the freeze conditioning process were appreciably greater than for the conventional chemical conditioning process. Further work on the project was suspended pending a thorough review of the process, engineering design, and economic aspects of the freeze conditioning project. This review substantiated the above conclusion. It was recommended that investigation of freeze conditioning be terminated and that the project objectives be redirected to the investigation of alternative sludge conditioning and dewatering means. This section of the report describes the work performed and results obtained prior to termination of the freeze conditioning investigation and redirection of the project objectives.

The work performed during the completed portion of the freeze conditioning investigation included (1) Determination of the process and design parameters and the (2) Engineering design and evaluation study.

Determination of the Process and Design Parameters

A literature search was made in the specific area of sludge conditioning by freezing methods (3)(4)(5)(6)(7)(8)(9)(10). The search, in conjunction with laboratory studies, was made to obtain the basic process and design parameters for prototype component design.

The literature search showed that the freeze conditioning method was applicable for various sewage plant sludges, such as, primary, activated and digested sludges. It was found that to obtain a significant conditioning action by the freezing method, the sludge must be completely frozen at relatively slow rates. Slush freezing, for example, produced little or no conditioning action. Addition of flocculating chemicals prior to freezing enhanced the dewatering rates after thawing.

Although the results obtained by the freeze-conditioning method were encouraging, development of the process was limited because

of (1) high cost and consumption of power, (2) high capital and operating costs when using conventional vacuum filter dewatering following freeze-conditioning, and (3) the need for frequent media washing when vacuum filtration was used following freeze-conditioning. Moreover, it was felt that the development of the freeze-conditioning method suffered from the necessity for batch operation. It was felt that the disadvantages may be overcome by utilizing gravity drain dewatering of freeze-conditioned sludge through relatively open-mesh media and by utilizing recent advancements in refrigeration design to produce a continuous freeze-conditioning operation. It appeared, therefore, that the successful application of the process was dependent upon pulling together an integrated engineering system which would be both economically feasible and practical.

Laboratory bench scale studies were conducted concurrently and in conjunction with the literature search. All tests were performed utilizing activated sludge from the Jones Island facilities of the City of Milwaukee Sewerage Commission.

Effect of Thickening

Activated sludge wasted from the Milwaukee Jones Island Treatment Plant is currently thickened by gravity to a concentration of about 1.5% to 2.0%. This waste activated sludge can be readily thickened to 4% solids or higher using dissolved-air flotation thickening at a solids loading of 10 lb/(day)(sq. ft.). It was necessary to determine whether the use of sludge with higher solids content would interfere in some unexpected manner with the observed improvement in dewaterability brought about by freezing. It was also felt that such prior thickening (from 1.5% to 4%+) would reduce the size and capital/operating costs of equipment required in subsequent freezing, thawing, and dewatering operations.

A series of tests was performed to determine the effect of initial sludge solids concentration on the dewatering characteristics of freeze-conditioned activated sludge. Return activated sludge samples having initial total solids concentrations of 1.1%, 2.1%, 3.3% and 5.3% were frozen overnight in 500 ml portions in a commercial chest type freezer. These sludges were then filtered through an 80 mesh screen after thawing at screen loadings of 0.25, 0.5 and 0.75 lb/sq ft. Finally, after filtration was completed, the filter cakes were mechanically pressed to remove additional free water. The results of the tests performed appear in Table 1. The following conclusions were drawn from an analysis of the data in Table 1.

TABLE 1

EFFECT OF INITIAL SLUDGE SOLIDS CONCENTRATION AND SCREEN SOLIDS LOADING ON THE DEWATERING CHARACTERISTICS OF FROZEN - THAWED ACTIVATED SLUDGE

Initial Sludge Solids (%)	Dewatering Property	Screen Solids Loading (lb/sq ft) 0.25	0.50	0.75
1.1	Filter Cake Solids (%)	17.2	16.1	14.2
	Filter Cake Solids (gm)	6.02	13.7	21.3
	Filtrate Suspended Solids(mg/l)	176	127	98
	Filtrate Suspended Solids (gm)	0.10	0.14	0.16
	Drain Time (Sec)	12	75	780
	Drain Rate (ml/sec)	44	14	1.7
2.1	Filter Cake Solids (%)	17.3	17.7	18.1
	Filter Cake Solids (gm)	6.75	15.9	24.1
	Filtrate Suspended Solids (mg/l)	377	348	198
	Filtrate Suspended Solids (gm)	0.10	0.18	0.16
	Drain Time (sec)	12	40	35
	Drain Rate (ml/sec)	21	12	22
3.3	Filter Cake Solids (%)	16.9	18.9	17.4
	Filter Cake Solids (gm)	5.41	10.4	20.5
	Filtrate Suspended Solids (mg/l)	607	437	343
	Filtrate Suspended Solids (gm)	0.10	0.15	0.16
	Drain Time (sec)	10	17	25
	Drain Rate (ml/sec)	14	21	18
5.3	Filter Cake Solids (%)	18.4	17.8	21.9
	Filter Cake Solids (gm)	4.23	13.5	19.5
	Filter Suspended Solids (mg/l)	1190	1175	560
	Filtrate Suspended Solids (gm)	0.12	0.20	0.16
	Drain Time (sec)	6	17	15
	Drain Rate (ml/sec)	12	8	17

1. Freeze-conditioning sludges having higher initial solids concentrations did not adversely affect the dewatering properties such as filter cake solids concentration, filtrate suspended solids, and filtrate drain rate. Although, for a given screen solids loading, the filtrate suspended solids concentration increased with increasing initial sludge solids concentration, the weight of filtrate suspended solids was relatively constant.

2. There was no apparent correlation between the above-mentioned dewatering properties and screen solids loadings.

3. Thickening of the plant sludge prior to freezing is feasible and will result in a reduction in the size of the refrigeration and dewatering equipment required as well as in a reduction in the capital and operating costs of refrigeration.

Therefore, flotation thickening of the feed sludge from the plant was incorporated as a process element in the freeze-conditioning system to be designed.

Freezing

Bench scale and field tests were performed to investigate the effect of the following freezing parameters on the dewatering properties of the thawed sludge.

1. Freezing Method

   The use of direct and indirect refrigeration means for freezing activated sludge were investigated. Direct refrigeration means (in which the refrigerant is in direct contact with the sludge), if successful, would have the advantage of eliminating the costly heat exchange surfaces associated with indirect refrigeration means. However, direct refrigeration means using such refrigerants as liquid nitrogen, methyl chloride, butane, isobutane, and freon were unsuccessful in that difficulties were encountered in freezing the sludge completely or the dewatering properties of the thawed sludge obtained were unsatisfactory. For example,

   a. Liquid Nitrogen

Two portions of waste activated sludge were rapidly frozen (within 20 seconds) using a liquid nitrogen bath. One portion was thawed immediately for dewatering tests on an 80 mesh screen. It did not dewater. The other frozen portion was stored in a 0° F freezer for 24 hours before thawing. This thawed portion also did not dewater on the 80 mesh screen. The appearance of both portions of freeze-conditioned sludges was identical to that of the unfrozen sludges.

b. Methyl Chloride (Boiling point, -11° F; liquid specific gravity, 0.998)

A hard porous ice structure having the appearance of a sponge formed at the interface between the sludge and the methyl chloride. Below the porous ice, which was one inch to 1.5 inches in depth, the sludge froze in a solid mass from the top down. When thawed, the porous ice structure did not dewater on the 80 mesh screen. The sludge below the porous ice dewatered poorly.

c. Freon 114 (boiling point 38.4° F; liquid specific gravity, 1.57)

The boiling point of Freon 114 was lowered to about 29° F by applying a vacuum of about 6.5 inches of mercury. Because Freon was heavier than the sludge, the Freon vapor passed through the sludge during the freezing process. This resulted in a porous ice structure which did not dewater well after thawing.

d. Butane (boiling point, 31° F; liquid specific gravity, 0.58)

Tests using butane were performed at reduced pressure to lower the boiling point. The sludge and butane were not mixed during the freezing process. Freezing took place from the top down, forming solid ice. As a result, great pressure was exerted by the advancing ice on the unfrozen sludge at the bottom. Many containers were ruptured before freezing was complete. Containers used in the methyl chloride tests broke in a similar fashion. Tests which were successful in completely freezing the sludge produced sludge which either did not dewater or dewatered poorly when thawed.

Freezing using direct refrigeration means was abandoned as the dewatering properties of the thawed sludge obtained were unsatisfactory.

Indirect refrigeration means (conventional vapor compression refrigeration cycles in which the refrigerant does not come into direct contact with the sludge) were successful in producing a frozen product, which when thawed, exhibited the desired dewatering properties. In the discussion which follows, freezing of the sludge was performed using indirect refrigeration means.

2. Effect of Sludge Storage Time before Freezing on Dewatering Properties

The effect of sludge storage time before freezing on the dewatering properties of the thawed sludge was evaluated using the data shown in Table 2. Sludge storage times of 0, 11, and 24 hours before freezing were investigated. The data shown in Table 2 were arranged into two groups, Tables 2A and 2B, in accordance with the number of days the sludge remained in the frozen state. (This variable significantly affects the thawed sludge dewatering properties and will be discussed separately, later.) The sludges for Table 2A remained in the frozen state for 4 days before thawing; those in Table 2B, 11 days. Dewatering tests were performed immediately after thawing.

It is evident from Tables 2A and 2B that cake solids concentration is adversely affected by storing the sludge before freezing. Moreover, the data show that drain time, drain rate, and filtrate suspended solids are not affected by sludge storage up to eleven hours, but may be detrimentally affected by storage of the liquid sludge for 24 hours before freezing.

Filtrate soluble phosphates and soluble COD increase with increased storage time before freezing. Although the data is not presented, most of this increase was observed to have occurred before freezing took place.

It was indicated from the results of these tests, therefore, that continuous feeding of flotation thickened sludge to the freezing operation would be desirable.

TABLE 2

EFFECT OF SLUDGE STORAGE TIME BEFORE FREEZING ON THE DEWATERING PROPERTIES OF THE THAWED SLUDGE

TABLE 2A

Age before freezing (hr)	0	11	24
Days frozen	4	4	4
Volume filtered (ml)*	475	490	495
Screen loading (lb/sq ft)	0.42	0.42	0.42
Drain time (sec)	19	18	35
Drain rate (ml/sec)	20	22	11
Cake solids (After pressing) (%)	18.3	17.5	14.9
Filtrate suspended solids (mg/l)	460	318	368
Filtrate soluble PO_4 (mg/l)	180	212	204
Filtrate COD (mg/l)	2644	3505	2971

TABLE 2B

Age before freezing (hr)	0	11	24
Days frozen	11	11	11
Volume filtered (ml)*	505	490	490
Screen loading (lb/sq ft)	0.42	0.42	0.42
Drain time (sec)	15	20	23
Drain rate (ml/sec)	27	20	17
Cake solids (After pressing) (%)	19.4	18.9	17.8
Filtrate suspended solids (mg/l)	200	200	260
Filtrate soluble PO_4 (mg/l)	--	162	182
Filtrate COD (mg/l)	--	3970	3833

* 80 mesh screen media used for gravity filtration.

3. Effect of Thawed Sludge Storage Time on Dewatering Properties

The effect of thawed sludge storage time on the sludge dewatering properties was evaluated using the data shown in Table 3. Thawed sludge storage times of 0, 8, and 24 hours were investigated.

The data in Table 3 show that cake solids concentration decreased with increasing storage time after thawing. In addition, filtrate soluble phosphates and soluble COD increased with increased age after thawing. However, filtrate suspended solids and drain rate appeared to be unaffected by thawed sludge storage up to 24 hours.

It is indicated, therefore, that it would be advantageous in full-scale operation to dewater the sludge as quickly as practicable after thawing.

4. Effect of Storage Time in the Frozen State on the Dewatering Properties

The effect of storage time in the frozen state on the sludge dewatering properties was evaluated using the data presented in Table 4. Data for storage times up to 28 hours are shown in Table 4. The sludge was frozen in 1/4" thick sheets (Table 4A) and in relatively large pint blocks (Table 4B).

The data in Tables 4A and 4B show that cake solids contents and drain rates are significantly benefited by frozen state storage times up to 16 hours.

It was indicated, therefore, that storage of sludge in the frozen state enhanced the dewatering properties of the thawed sludge. However, although frozen sludge storage is desirable from a process standpoint, it was felt to be impractical on a full scale basis (for example, at Milwaukee, about three million gallons of waste activated sludge are processed daily).

5. Effect of Freezing Time on the Dewatering Properties

Times for complete freezing were varied from a matter of seconds to 16 hours. Fast freezing, such as with liquid nitrogen, produced no improvement in the dewatering properties after thawing.

TABLE 3

EFFECT OF THAWED SLUDGE STORAGE TIME ON THE SLUDGE DEWATERING PROPERTIES

Time after thawing (hr)	0	8	8	24	24
Days frozen	4	4	6	4	6
Volume filtered (ml)*	475	485	482	485	475
Screen loading (lb/sq ft)	0.40	0.41	0.41	0.41	0.41
Drain time (sec)	19	22	21	26	23
Drain rate (ml/sec)	20	18	18	15	17
Calse solids (After pressing) (%)	18.3	--	17.4	--	16.7
Filtrate suspended solids (mg/1)	460	381	185	518	445
Filtrate soluble PO_4 (mg/1)	180	212	210	288	246
Filtrate COD (mg/1)	2644	3223	3452	4029	3884

* 80 mesh screen media used for gravity filtration.

TABLE 4

EFFECT OF STORAGE TIME IN THE FROZEN STATE ON THE DEWATERING PROPERTIES OF THE THAWED SLUDGE

A. Freezing in trays (¼" thick layers)

Time to freeze (hr)	2	1.5	3	3
Storage after freezing (hr)	0	4	16	24
Feed sludge solids (%)	2	2	2	2
Volume filtered (ml)*	474	491	479	482
Screen loading (lb/sq ft)	0.33	0.35	0.33	0.34
Drain time (sec)	--	43	36	29
Drain rate (ml/sec)	--	8	10	12
Cake solids (After pressing) (%)	10.8	12.2	14.4	14.3

B. Freezing in pint boxes (3¼" x 3¼" x 2¼")

Time to freeze (hr)	7	8	8.5
Storage after freezing (hr)	4	16	28
Feed sludge solids (%)	2	2	2
Volume filtered (ml)*	495	497	478
Screen loading (lb/sq ft)	0.35	0.35	0.33
Drain time (sec)	48	24	24
Drain rate (ml/sec)	6	16	17
Cake solids (After pressing) (%)	13.5	15.2	15.5

* 80 mesh screen media used in gravity filtration.

The effect of freezing time on the thawed sludge dewatering properties was evaluated from data such as that presented in Table 5. The data shown were generated from tests performed by freezing sludge in pint blocks. The data in Table 5 show that, from the standpoint of drain time, drain rate, and cake solids, a freezing time of ten hours was optimum for a storage period after freezing of one day.

In general, it was indicated that the dewatering properties of the thawed sludge improved as the freezing time increased. From a practical standpoint, however, the size of the freezer, and, therefore, the volume requirements and capital costs of the freezing equipment increase with increasing freezing time. In this regard, a sacrifice in dewatering quality may have to be considered in order to minimize equipment capital costs.

6. Partial Freezing

Bench tests and field tests showed that, in order to be effective, the freezing of the sludge must be complete. Any small volume of unfrozen sludge (a few milliliters in 500 ml, for example) was sufficient to cause a marked adverse effect on the dewatering properties of the thawed sludge. These observations appeared to eliminate the use of slush ice machines, which are readily available on the market.

Moreover, partially freezing the sludge and discarding the unfrozen portion prior to thawing was not effective. The partially frozen portion of the sludge dewatered poorly, if at all, upon thawing. This eliminated those commercial machines capable of producing frozen sludge in this manner.

7. Mobility of Sludge During Freezing

A field trip was made to the Turbo Refrigerating Company in Denton, Texas for the purpose of field testing their refrigeration equipment in the freezing of activated sludge. The operating principle of the Turbo machine consists of flowing a sheet of the liquid to be frozen down a vertical cold plate. Waste activated sludge from the nearby Denton, Texas Water Pollution Control Plant was used in the field test. The results of the field test, both visual and from analysis of samples obtained,

TABLE 5

EFFECT OF FREEZING TIME ON THE DEWATERING

PROPERTIES OF THE THAWED SLUDGE

Time to freeze (hr)	3	4	9	10	11	16
Storage after freezing (hr)	24	24	24	24	24	24
Feed sludge solids (%)	2.46	2.46	2.46	2.23	2.23	2.46
Volume filtered (ml)*	495	492	493	502	440	502
Screen loading (lb/sq ft)	0.43	0.43	0.43	0.40	0.35	0.44
Drain time (sec)	300	57	28	20	25	33
Drain rate (ml/sec)	1	6	13	20	14	11
Cake solids (After pressing) (%)	11.7	12.1	13.9	14.1	14.1	12.6

* 80 mesh media used in gravity filtration.

showed that essentially only the water associated with the feed sludge was frozen on the vertical cold plates. The unfrozen sludge flow from the plates, of course, was more concentrated (2% solids) than the feed sludge (1% solids).

The results of the field test conducted indicated that there should be no relative motion between the sludge to be frozen and the freezing medium. It appeared, therefore, that ice machines operating on the Turbo principle (liquid sludge flowing over a stationary cold plate) or ice machines in which the freezing medium travels through the liquid sludge (such as a cold drum rotating in a vat of liquid sludge) would not be applicable for freeze-conditioning of sludges.

8. Chemical Additives

Chemical additives were investigated to determine their effect as adjuncts to the freeze-conditioning method. Ferric chloride was the additive found to give the most pronounced beneficial effect in this study. The effect of ferric chloride was investigated when added to the sludge before freezing and when added to the thawed sludge after freezing. The data obtained from the tests performed are presented in Tables 6 and 7.

In Table 6 are shown the results obtained from the addition of about 28 and 55 lb/ton of ferric chloride before freezing. Note the appreciable decrease is soluble phosphate before freezing caused by the addition of ferric chloride. This was expected. After freezing, thawing and gravity filtration, it is evident that from Table 6 the filtrate soluble phosphate contents obtained were consistently and appreciably greater than the corresponding soluble phosphate contents before freezing. It is speculated that the increase observed was a result of cell rupture during the freezing process and subsequent release of phosphorus into solution. However, the filtrate soluble phosphate contents of the chemically dosed samples were appreciably less than that for the control sample (zero ferric chloride).

Referring to Table 6, the addition of the amounts of ferric chloride shown improved the screened cake concentration, drain rate, and filtrate suspended solids. Moreover, the soluble COD in the filtrate was reduced as a result of chemical addition.

In Table 7 are shown the results of the tests performed from the addition of about 27 and 54 lb/ton of ferric chloride after freezing and thawing and before gravity filtration. Note that the filtrate soluble phosphate contents for the control (zero ferric chloride) and 27.1 lb/ton ferric chloride samples were greater than the corresponding soluble phosphate contents before freezing. However, the ferric chloride dosage of 54.2 lb/ton was sufficient to appreciably reduce the filtrate soluble phosphate content (90 mg/l) from that observed in sludge prior to freezing (140 mg/l). Again, the filtrate soluble phosphate content in the chemically treated samples were lower than that observed in the control sample.

Referring to Table 7, the addition of about 27 and 54 lb/ton ferric chloride after thawing adversely affected the drain rate, drain time and filtrate suspended solids. The cake solids concentration was not improved, but lower filtrate soluble COD's were obtained as a result of the chemical treatment.

In summary, ferric chloride was found to beneficially affect the sludge dewatering properties when introduced into the sludge before freezing. Introducing ferric chloride into the sludge after thawing adversely affected the dewateri roperties of the thawed sludge.

9. Shape of Configuration of the Sludge to be Frozen

Shapes and configurations investigated included relatively large blocks, small cubes, and relatively thin sheets. Bench scale and field tests were performed to evaluate the effect of these shapes.

Most of the data presented thus far was obtained from tests performed by freezing the sludge in relatively large blocks. In general, freezing in large blocks or cubes in inherently slow and was felt to adversely affect production rate. For example, as the freezing of blocks progresses, the area for heat transfer and the overall heat transfer coefficient decrease, resulting in a progressive decrease in the freezing rate. Furthermore, the rate of thawing is slow because of the relatively low surface area to volume ratio involved.

On the other hand, when freezing in relatively thin sheets, the area for freezing and the overall heat transfer coefficient remain essentially constant during

TABLE 6

EFFECT OF THE ADDITION OF FERRIC CHLORIDE BEFORE FREEZING ON THE SLUDGE DEWATERING PROPERTIES

Ferric chloride dosage (lb/ton)	0	0	28.3	28.3	54.8	54.8
Days sludge frozen	2	7	2	7	2	7
Feed sludge solids (%)	2.36	2.36	2.36	2.36	2.36	2.36
Soluble PO_4 before freezing (mg/l)	140	140	84	84	46	46
Screen loading (lb/sq ft)*	0.44	0.44	0.42	0.44	0.43	0.44
Drain time (sec)	37.5	23	30	21	23.5	26
Drain rate (ml/sec)	8.1	16.3	11.4	18	15.2	14.4
Cake solids (After pressing) (%)	14.3	16.3	16.1	16.6	17.2	16.3
Filtrate suspended solids (mg/l)	90	270	75	240	60	280
Filtrate soluble PO_4 (mg/l)	202	--	152	--	100	--
Filtrate soluble COD (mg/l)	3220	5303	2440	4837	2407	5056

* 80 mesh screen media used for gravity filtration.

TABLE 7

EFFECT OF THE ADDITION OF FERRIC CHLORIDE AFTER FREEZING AND THAWING ON THE SLUDGE DEWATERING PROPERTIES

Ferric chloride dosage (lb/ton)	0	27.1	54.2
Days sludge frozen	2	2	2
Feed sludge solids (%)	2.36	2.36	2.36
Soluble PO_4 before freezing (mg/l)	140	140	140
Screen loading (lb/sq ft)*	0.44	0.43	0.45
Drain time (sec)	37.5	40	90
Drain rate (ml/sec)	8.1	7.6	3.3
Cake solids (After pressing) (%)	14.3	14.6	13.2
Filtrate suspended solids (mg/l)	90	190	105
Filtrate soluble PO_4 (mg/l)	202	152	90
Filtrate soluble COD (mg/l)	3220	3054	2805

* 80 mesh screen media used for gravity filtration.

the freezing process. Thin sheet freezing also has the following advantages over freezing in blocks: (1) Thin sheets lend themselves more readily to a continuous freezing process, (2) By breaking the frozen sheets into small chards, more surface area per unit volume for faster thawing may be obtained, and (3) Faster feedback information is available for process quality control, (4) Faster freezing times per unit weight of sludge frozen may be used, resulting in lower equipment costs.

As a result of the above analysis, it was felt that, if the freezing cycle could be shortened and storage after freezing eliminated, the economics of freeze conditioning would be improved. Therefore, an investigation into the various aspects of thin sheet freezing was launched. Bench scale sheet ice tests were performed by placing the sludge in shallow pans and freezing the sludge in an upright freezer having a forced air draft and suitable control over freezer temperature to permit varying freezing times. Freezing time was accurately measured using recording thermocouples, strategically placed in the sludge layer. A time-temperature record was obtained for each test, and the freezing time was obtained from the constant temperature (32° F) portion of the curve.

The ice layer depths investigated included 1/8", 1/4", 1/2" and 1" and greater. It was noted that freezing in one inch and greater ice depths resulted in pan container deformation. Therefore, these ice depths were eliminated from consideration for prototype design.

Thawed sludges derived from relatively fast freezing were sensitive to handling, and this sensitivity to handling increased with decreasing freezing times. Good sludge dewatering properties were observed at the fast freezing times when handling of the thawed sludge prior to gravity filtration was reduced to a minimum. In contrast, control samples, which were handled in the normal manner (inverting the thawed sludge twice in a graduate prior to pouring into a gravity drain filter apparatus), did not dewater at all.

Dewatering of the thawed sludge was carried out by allowing it to gravity drain on an 80 mesh screen filter medium followed by further dewatering on the screen using either a 5" Hg vacuum or by mechanical pressing. Vacuum was selected as the further dewatering means because of its

relative success in handling the wide range of cake characteristics obtained in the investigation.

Shown in Figure 1 are typical results obtained using relatively fast freezing in thin sheets. Waste activated sludge was used. Freezing times and screen loadings after thawing for the ice layer depths shown in Figure 1 were:

Ice Layer Depth (in)	Freezing Time (minutes)	Screen Loading (lb/sq ft)
1/8	15	0.15
1/4	40	0.15
1/2	90	0.14
1	180	0.13

The results shown in Figure 1 were obtained from tests in which the frozen sludge was not stored prior to thawing, a minimum of handling was exercised after thawing, and a 20 second vacuum at 5 in Hg was used following gravity drain on an 80 mesh screen.

Referring to Figure 1, at zero ferric chloride dosage (no chemicals), relatively good dewatering properties were observed at fast freezing times and minimum handling after thawing. In contrast, control samples, which were handled in the normal manner after thawing (inverting the thawed sludge twice in a graduate) did not dewater at all. It is noted in Figure 1 (no chemicals) that a significant increase in cake solids content was obtained when the ice layer depth was increased above one-eighth inch.

Presented also in Figure 1 is the effect of adding nominal amounts of ferric chloride on cake solids content. (Note: Ferric chloride added before freezing). In general, it was observed that, for a given ice layer depth, an increase in ferric chloride dosage resulted in an increase in cake solids content. It was also observed that the addition of ferric chloride also permitted rougher handling of the sludge after thawing.

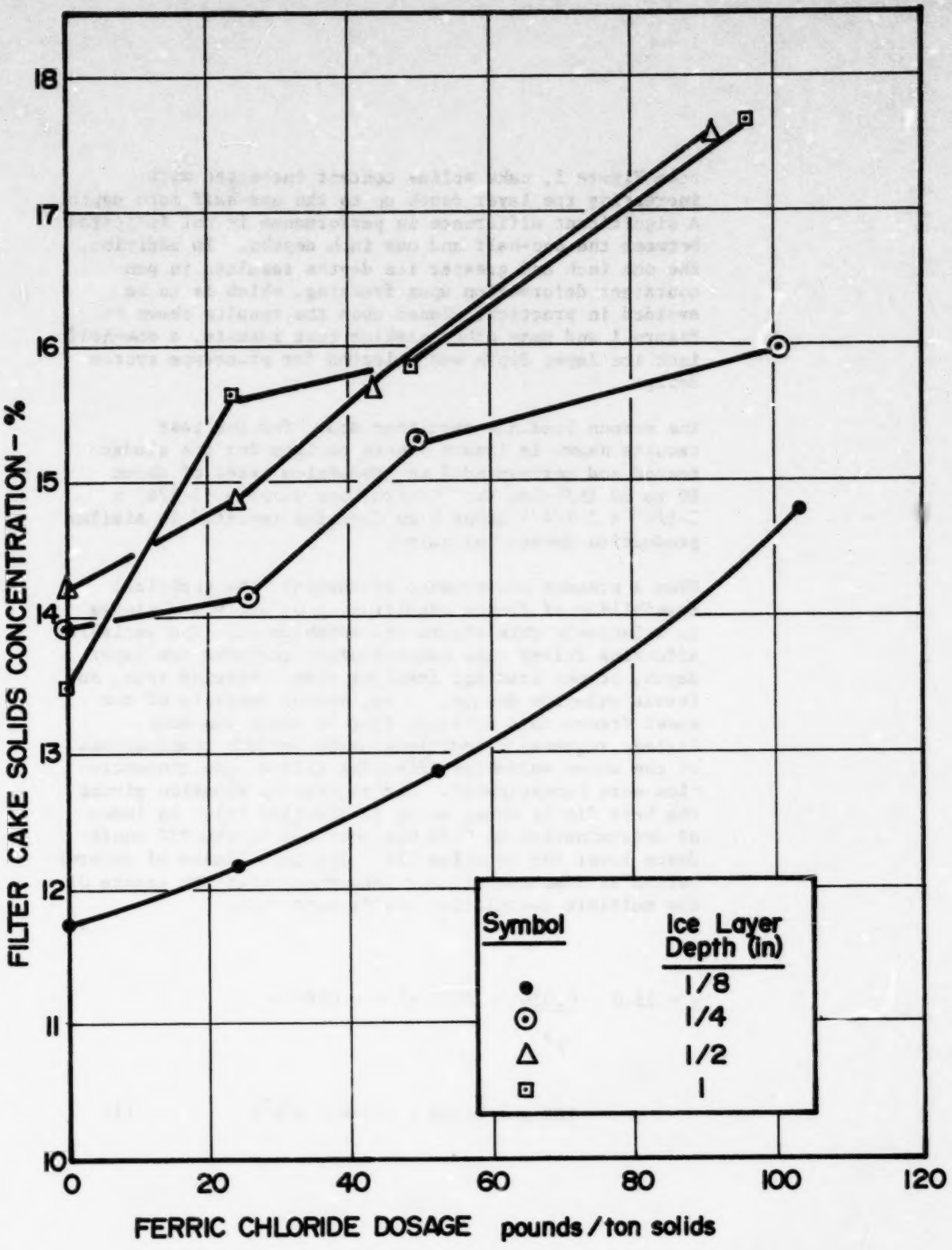

FIGURE I. EFFECT OF FERRIC CHLORIDE ON CAKE SOLIDS

From Figure 1, cake solids content increased with increasing ice layer depth up to the one-half inch depth. A significant difference in performance is not indicated between the one-half and one inch depths. In addition, the one inch and greater ice depths resulted in pan container deformation upon freezing, which is to be avoided in practice. Based upon the results shown in Figure 1 and many other similar test results, a one-half inch ice layer depth was selected for prototype system design.

The screen loadings tabulated above for the test results shown in Figure 1 were optimum for the sludge tested and corresponded to production rates of about 10 to 20 lb/hr/sq ft. Control box samples (3-1/4" x 3-1/4" x 2-1/4") using slow freezing resulted in similar production dewatering rates.

From a process performance standpoint, the technical feasibility of freeze conditioning of activated sludge in relatively thin sheets was established. The variables affecting filter cake concentration included ice layer depth, screen loading, freezing time, freezing rate, and ferric chloride dosage. A regression analysis of the sheet freeze data obtained from 46 tests was made. Sixteen regression equations using various combinations of the above variables affecting filter cake concentration were investigated. The regression equation giving the best fit is shown below in Equation (1). An index of determination of 0.88 was obtained at the 99% confidence level for Equation (1). The term "index of determination" is identical to and synonymous with the square of the multiple correlation coefficient (12).

$$\chi = 15.0 - \frac{0.026}{y^2} - 24.6\, z^2 + 0.0082\, w$$

$$- 182\, s + 0.028\, c + 4193\, z^2 s^2 c \qquad (1)$$

Definitions of the variables used in Equation (1) and the ranges of those variables are listed below.

χ = cake concentration, %

y = ice layer depth (1/8 in - 1 in)

z = screen loading (0.1-0.37 lb/sq ft)

w = freezing time (20 - 336 min)

s = freezing rate (0.0015 - 0.0122 in/min)

c = ferric chloride dosage (0 - 104 lb/ton)

The dewatering operating conditions implied for Equation (1) include minimum handling of the sludge after thawing, gravity drain on an 80 mesh screen medium, and a 20 second vacuum at 5 in Hg following gravity drain.

Similarly, an expression was developed for calculating the required gravity drain time. The sheet freeze data from 46 tests were used in the regression analysis. The regression equation yielding the best fit is shown in Equation (2), below.

$$t = 8.5 - 19.6y + 393z^2 - 0.39c + 2280s + 0.044\frac{c}{z} \quad (2)$$

where, t = gravity drain time, sec.

The other variables in Equation (2) are as defined for Equation (1). The dewatering operating conditions implied for Equation (2) include minimum handling of the sludge after thawing, and gravity drain on an 80 mesh screen medium.

Equations (1) and (2) may be used in selecting the process and design parameters for a prototype thin ice-sheet freeze-conditioning system. The variables affecting cake solids concentration and gravity drain time included ice sheet depth, screen loading, freezing time, freezing rate, and ferric chloride concentration.

Engineering Design and Evaluation Study

Emerging from the preliminary investigation described above and carried forward to the engineering design phase of the project was a freeze-conditioning system consisting of the following process elements:

1. Flotation thickening prior to freezing
2. Freezing in thin sheets
3. Thawing of the frozen product
4. Dewatering of the thawed sludge
5. Optional use of ferric chloride prior to freezing.

A schematic diagram of the system is shown in Figure 2.

The freeze conditioning demonstration pilot plant, to be installed in the Machinery Bay building of the Milwaukee Water Pollution Control Plant, was intended to handle three dry tons activated sludge solids per day using a feed sludge solids concentration of 1% to 2%.

Design of the 3 Dry Ton/Day Pilot Plant Flotation Thickener

The flotation thickening step was incorporated into the freeze-conditioning process for the purpose of concentrating the feed sludge from 1% to 2% to a thickened sludge concentration of 4%. Thickening was to be accomplished using the dissolved-air flotation principle. The process elements associated with flotation thickening include (1) pressurization (40 psig) of plant final effluent or recirculated thickener effluent, (2) air introduction (about one standard cubic foot per 100 gallons of pressurized flow), (3) air solution at the elevated pressure (4) pressure reduction and tiny (about 100 micron) bubble formation, (5) blending of air-charged stream and feed sludge flow, (6) air-bubble-solids attachment, (7) solids-liquid separation, (8) separated solids compaction or thickening, and (9) thickened sludge and clarified effluent removal.

The thickening step described above was expected to result in the removal, prior to freezing, of 50% or more of the water associated with the feed sludge solids. It was felt that the operating cost of removing this quantity of water by flotation thickening was significantly less than the cost of freezing the water removed by thickening. Moreover, the savings in freezer system and thawing system capital costs brought about by the thickening step were also expected to be significant.

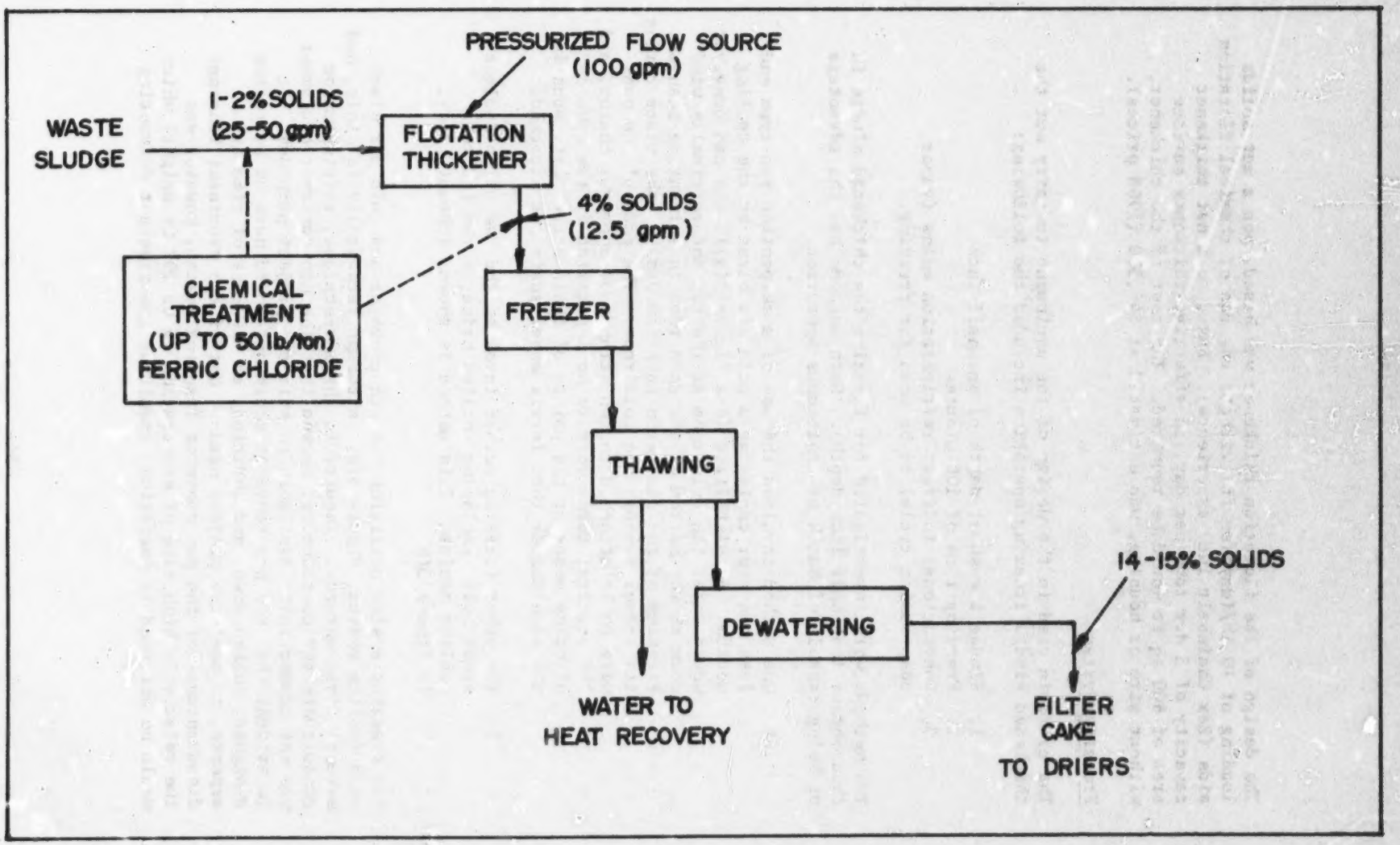

FIGURE 2. SCHEMATIC DIAGRAM OF THREE TON DRY SOLIDS PER DAY FREEZE-CONDITIONING SYSTEM

The design of the flotation thickener was based upon a net solids loading of 10 lb/(day)(sq ft) without the use of chemical flotation aids (Rex Chainbelt Inc. experience). Based on a net thickener capacity of 3 dry tons per day, an effective thickener surface area of 600 sq ft would be required. The cost of the thickener, without site or housing, was estimated at $46,500 (1968 prices).

Freezing System

The criteria used in the design of the equipment to carry out the thickened sludge freezing operation included the following:

1. Sludge ice-sheet depth of one-half inch
2. Freezing time of 100 minutes
3. Conventional indirect refrigeration means (vapor compression cycle) to be used for freezing.

Two methods were investigated for freezing the thickened sludge in thin sheets (one-half inch depth). Both methods had the advantage of being capable of batch or continuous operation.

1. One method involved the use of a serpentine pan-type endless conveyor employing a cold air blast as the cooling medium. As visualized (See Figure 3(a)), the pan conveyor would enter the cold room at the top and vertically wind down to the bottom of the cold room in serpentine fashion. Freezing of the sludge in each pan was to take place during its travel through the cold room. The ends of the pans were to be attached to two strands of conveyor chains, and the vertical turns were to be negotiated by the pans by pivoting means at the points of chain attachment, much in the same manner that ferris wheel seats are attached.

2. The other freezing method involved the use of an endless steel belt, employing chilled brine as the indirect cooling medium. This method is shown, schematically, in Figure 3(b).

The freezing system utilizing the pan conveyor and cold air blast as a cooling medium, Figure 3(a), although technically feasible, had several disadvantages. Inquiry in the marketplace, refrigeration consultants and contractors, showed that the pan conveyor equipment was not commercially available to suit the project purposes. It is evident that the pan conveyor equipment would have to be custom designed, shaken down, and modified, at the cost of time and expense, to meet the project needs. One of the prominent inherent disadvantages of the pan conveyor freezing system, however was the relatively high rate of evaporation (5 to 10% by weight) which would be obtained in operation, requiring too frequent defrosting

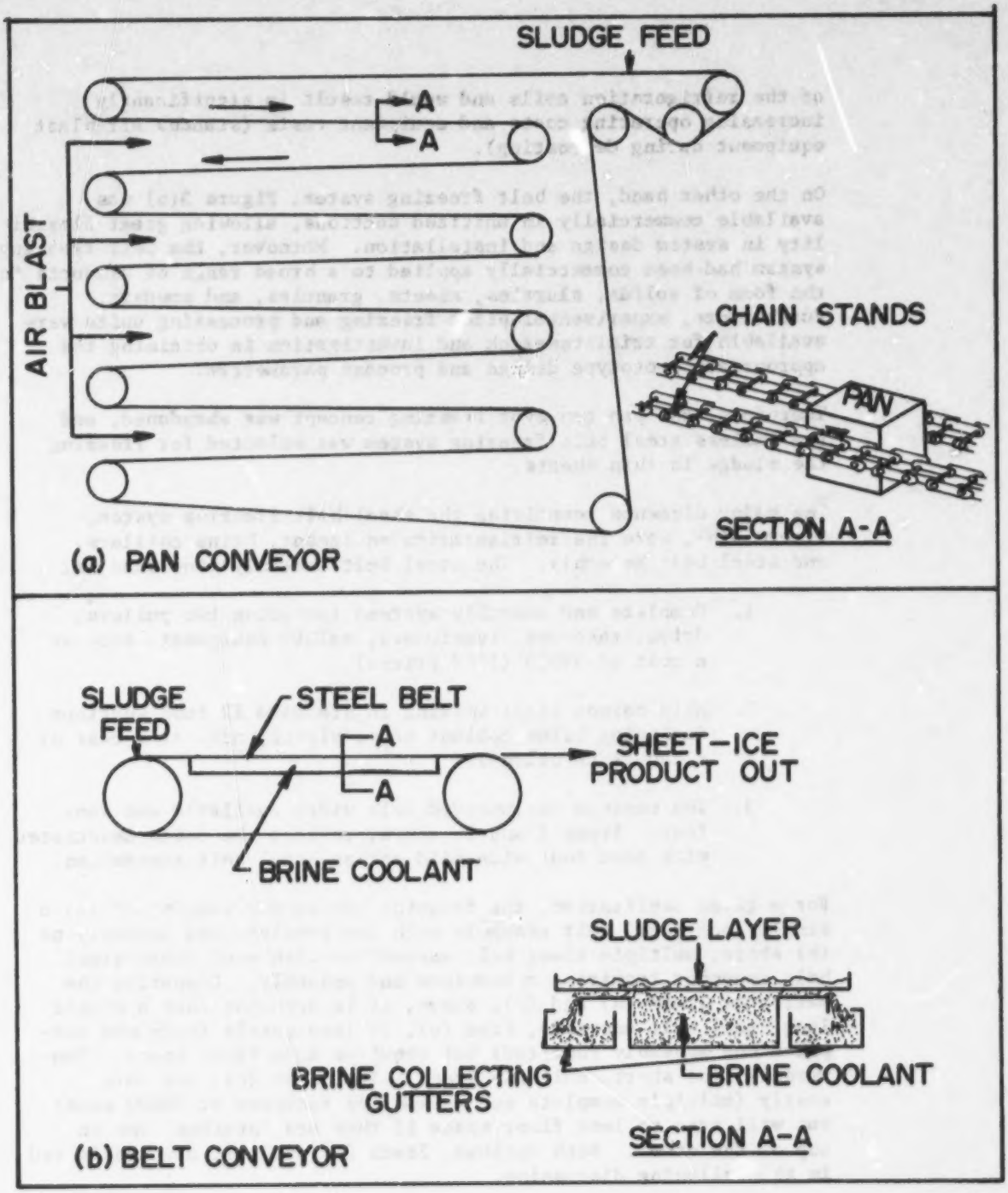

FIGURE 3. TWO METHODS INVESTIGATED FOR FREEZING THICKENED SLUDGE

of the refrigeration coils and would result in significantly increasing operating costs and equipment costs (standby air-blast equipment during defrosting).

On the other hand, the belt freezing system, Figure 3(b) was available commercially in unitized sections, allowing great flexibility in system design and installation. Moreover, the belt freezing system had been commercially applied to a broad range of products in the form of solids, slurries, sheets, granules, and powders. Furthermore, experimental pilot freezing and processing units were available for trial research and investigation in obtaining the appropriate prototype design and process parameters.

Therefore, the pan conveyor freezing concept was abandoned, and the endless steel belt freezing system was selected for freezing the sludge in thin sheets.

The major elements comprising the steel belt freezing system, Figure 3(b), were the refrigeration equipment, brine chillers, and steel belt assembly. The steel belt assembly consisted of,

1. Complete end assembly systems including two pulleys, drive, take-ups, tensioners, safety equipment, etc. at a cost of $8600 (1968 prices).

2. Mild carbon steel belting in standard 12 foot sections including brine coolant pans, piping, etc. at a cost of $2100 (1968 prices).

3. The maximum recommended belt width available was four feet. Items 1 and 2, above, reflect the costs associated with four foot wide mild carbon steel belt assemblies.

For a given application, the freezing system may consist of (a) a single long steel belt assembly with one complete end assembly or (b) short, multiple steel belt assemblies with each short steel belt conveyor requiring a complete end assembly. Comparing the merits of Items (a) and (b), above, it is apparent that a single long steel belt assembly, Item (a), is less costly (only one complete end assembly required) but requires more floor space. Conversely, the short, multiple steel belts, Item (b), are more costly (multiple complete end assemblies required at $8600 each) but will take up less floor space if they are "stacked" one on top of the other. Both options, Items (a) and (b), are considered in the following discussion.

The major equipment costs as well as the floor space requirements for the two alternative belt freezing systems handling three dry

tons of sludge solids per day at a thickened feed sludge solids content of 4% are presented below. The major equipment costs include erection but exclude site and housing costs because these were available at the Milwaukee Plant. Details of the calculations used in arriving at the tabulated figures are presented in Appendix A.

Belt Conveyor System	Effective Floor Space Required (sq ft)	Major Equipment Cost ($)
Single Belt	4713	551,000
Multiple Belt	1227	883,900

Thawing System

The frozen sludge obtained from the belt conveyor freezer system was to be melted on a suitable thawing conveyor prior to further dewatering. The frozen sludge sheet from the freezing system was to be broken up into small shards and discharged onto the thawing conveyor consisting of a relatively coarse (40 x 60 mesh openings) porous medium. The porous medium permits the melted ice water to drain off and be utilized as a refrigeration condenser cooling source and/or heat exchanged with the incoming thickened feed sludge to the sludge freezing system.

The source of heat for thawing the frozen sludge was to be that recovered from the refrigeration system (heat of vaporization and heat of compression) and from auxiliary heat sources, as required. The heat required for thawing was to be transferred to the frozen sludge, using air as the medium, by heater blowing equipment. Provision for washing the conveying medium was also to be made.

The major components comprising the thawing system included the conveyor medium, drives, pulleys, take-ups, blowers, wash pump, ice water collection through, and insulation. The major equipment costs as well as the floor space requirements for the thawing system are tabulated below. The equipment costs include erection costs but exclude the cost of site and housing as these were available at the Milwaukee Plant. Details of the calculations used in designing the thawing system are presented in Appendix B.

Effective floor area required = 1632 sq ft
Thawing system equipment cost = $65,000

Thawed Sludge Dewatering System

The thawed sludge obtained was expected to contain substantial amounts of free water and the major portion of this water was to be removed by a final dewatering step. It was intended to carry out the dewatering of the thawed sludge by allowing it to gravity drain on an 80 mesh screen filter medium followed by further dewatering on the screen using a 5" Hg vacuum.

The equipment required to carry out the final dewatering step was commercially available in the form of a horizontal belt filter. The major equipment costs and floor space requirements for the dewatering system are shown below. The equipment costs include erection costs but exclude the cost of site and housing as these were available at the Milwaukee Plant. Details of system design for the dewatering system are presented in Appendix C.

Effective floor area required = 24 sq ft
Dewatering system equipment costs = $16,800

Chemical Treatment System

Chemical additives were investigated for their effect as adjuncts to freezing on the dewatering properties of the thawed sludge. Ferric chloride was the additive found to give the most pronounced beneficial effect in this study. Up to 50 lb per ton ferric chloride was used effectively when introduced into the sludge before freezing. Therefore, provision for the optimal use of ferric chloride prior to sludge freezing was to be incorporated in the freeze-conditioning demonstration plant.

The major components comprising the chemical treatment system included the chemical stock storage tank and supporting base, mixer, and chemical feed pump. The major equipment costs and the floor space requirements for the chemical treatment system are listed below. Again, site and housing are not included in the cost listed as these were available at the Milwaukee Plant. Details of the design of and cost breakdown for the chemical treatment system are presented in Appendix D.

Effective space requirements = 16 sq ft
Equipment costs = $1100

Summary of the Equipment Costs and Floor Space Requirements for the Three Ton Solids Per Day Freeze-Conditioning Demonstration Plant

A summary of the major equipment costs and floor space requirements for the freeze-conditioning demonstration plant is presented in Table 8. It is evident from Table 8 that the alternative utilizing a single freezing belt conveyor is less costly but requires greater floor space than the alternative using the multiple belt freezing conveyor system.

Comparison of Freeze-Conditioning and Conventional Chemical Conditioning Methods

At this point, it was deemed appropriate to compare the freeze-conditioning process with the conventional chemical conditioning method from the standpoint of equipment costs and floor space requirements. The chemical conditioning process used as a basis for comparison is the one presently employed by the Milwaukee Water Pollution Control Plant, namely, ferric chloride conditioning of waste activated sludge followed by vacuum filtration dewatering. Cost figures include the cost of the dewatering step, which is carried out using horizontal screen belt filters for the freeze-conditioning method and using rotary vacuum filters for the conventional chemical conditioning method.

The estimated effective space requirements and equipment costs for the major components of the freeze-conditioning (from Table 8) and conventional chemical conditioning systems, handling 3 tons dry solids per day of waste activated sludge are shown in Table 9. The equipment costs shown for freeze-conditioning do not include site or housing whereas those shown for conventional chemical conditioning include the cost of site and housing. The equipment costs for conventional chemical conditioning were obtained from Smith (11).

A comparison of the estimated effective space requirements for the two sludge conditioning methods presented in Table 9 shows that the space requirements for the freeze-conditioning system (utilizing the single belt conveyor freezer) are about 130 times that required for the existing conventional chemical conditioning system. The ratio of 130:1 may be reduced to 65:1 by utilizing a multiple belt conveyor freezer in the freeze-conditioning system.

It is concluded, therefore, that from a space requirement standpoint, the freeze-conditioning process does not compare favorably with the existing conventional chemical conditioning process.

TABLE 8

SUMMARY OF THE EQUIPMENT COSTS* AND FLOOR SPACE REQUIREMENTS FOR THE THREE TON SOLIDS PER DAY FREEZE-CONDITIONING DEMONSTRATION PLANT

Process Element	Space Requirements (sq ft)	Equipment Cost ($)
1. Flotation Thickener	600	46,500
2. Freezing System		
a. Single Belt Conveyor	4,713	551,000
b. Multiple Belt Conveyor	1,227	883,900
3. Thawing System	1,632	65,000
4. Thawed Sludge Dewatering	24	16,800
5. Chemical Treatment System	16	1,100
6. Totals		
a. With Single Belt Conveyor Freezing System	6,985	680,400
b. With Multiple Belt Conveyor Freezing System	3,509	948,300

*Not including site or housing

Examination of the demonstration site showed that it was physically impractical to install a 3 ton/day freeze conditioning system at the Milwaukee Water Pollution Control Plant. Moreover, for the space available, it would be necessary to reduce the capacity of the pilot plant from 3 ton/day to 0.25 tons/day in order to fit in a freeze conditioning demonstration pilot plant at Milwaukee.

A comparison of the estimated equipment costs for the two sludge conditioning methods presented in Table 9 shows that the costs for the freeze-conditioning system (utilizing the multiple belt conveyor freezer) are about ten times the costs for the existing conventional chemical conditioning system. The cost ratio of 10:1 may be reduced to 7:1 by utilizing a single belt conveyor freezer in the freeze conditioning system. The cost ratios cited, in favor of the conventional chemical conditioning process should actually be greater because the freeze-conditioning system costs listed in Table 9 do not include the cost of site and housing.

It is concluded, therefore, that the major equipment costs are appreciably greater for the freeze-conditioning process than for the conventional chemical conditioning process.

It was estimated that the lowest cost of a 3 ton/day freeze-conditioning pilot plant (without site or housing) (Table 9) would be $680,400. This cost is greater than the total estimated project cost, which was $348,344. Furthermore, if the design capacity of the freeze conditioning pilot plant were reduced to 0.25 tons/day, the cost of the pilot plant would be about $140,900. At the 0.25 tons/day capacity, it may be shown that additional monies over and above those originally granted would be required to complete the project work and to achieve the objectives of the project.

Application and Evaluation of the Freeze-Conditioning Process to Large Scale Plants

Extrapolation of data for 1/4, 1/2, 1, and 3 tons/day plants indicates that the cost of a freeze-conditioning plant handling 200 tons solids per day (roughly that presently handled by the Milwaukee Plant) would be about 80.0 million dollars (multiple belt conveyor freezer). The above costs cited are without site or housing and reflect 1968 prices.

On the other hand, it is estimated that a conventional chemical conditioning plant, handling 200 tons solids per day, would cost 5.1 million dollars (11). This cost reflects 1968 prices and includes housing and installation.

TABLE 9

COMPARISON OF EQUIPMENT COSTS AND FLOOR SPACE REQUIREMENTS FOR THE FREEZE-CONDITIONING AND CONVENTIONAL CHEMICAL CONDITIONING METHODS*

Conditioning System	Equipment Costs ($)	Space Requirements (sq ft)
1. Freeze-Conditioning (Table 8)		
a. Single Belt Conveyor Freezing System	680,400	6,985
b. Multiple Belt Conveyor	948,300	3,509
2. Conventional Chemical Conditioning System**	95,000	54

*Based on handling 3 dry tons solids/day of waste activated sludge

**Vacuum filtration at a yield of 1.5 lb/(hr)(sq ft)
Filter dimensions = 9 foot diameter x 6 foot face
Equipment costs include site and housing

It is concluded that the capital or construction costs for both small and large plants are appreciably greater for the freeze-conditioning process than for the conventional chemical conditioning process.

Comparison of Operating Costs for the Freeze Conditioning and Chemical Conditioning Processes

An examination of the operating costs for the two sludge conditioning processes showed that the operating costs for the freeze-conditioning process were appreciably greater than those for the chemical conditioning process. For example, the operating costs for the two processes were investigated for the existing Milwaukee plant handling 238 tons solids per day. The results of this comparison are shown in Table 10. It is noted in Table 10 that the detailed operating costs shown include labor maintenance, chemical costs, power, and amortized capital costs (20 year life, 3%). The operating costs shown for the ferric chloride conditioning process were the actual costs incurred by the Milwaukee Plant in the year, 1966, whereas the freeze-conditioning costs were on an estimated basis. The operating costs obtained varied from about $77 to $79 per ton of dry solids processed.

Investigation of the Possibility of Reducing the Operating Costs of Freeze-Conditioning

Evaluation of the freeze-conditioning process and comparison with the existing conditioning method presently employed at Milwaukee showed that the capital and operating costs and space requirements were appreciably greater for the freeze-conditioning process than for the existing chemical conditioning method.

An aspect of the engineering design study that was investigated was the reduction of the freeze-conditioning process operating costs by appreciably reducing the amount of refrigeration work required. In this regard, a technical audit of the freeze-conditioning system was conducted with the Massachusetts Institute of Technology, Cambridge, Massachusetts. The purpose of the consultation, particularly, was to investigate the aspect of energy recovery and energy conservation. As a result of this audit, it was concluded that other refrigeration methods could be applied that require less power per unit of sludge frozen, but that these methods will likely prove to have substantially higher capital costs.

TABLE 10

COMPARISON OF OPERATING COSTS FOR FERRIC CHLORIDE AND FREEZE-CONDITIONING OF MILWAUKEE WASTE ACTIVATED SLUDGE (238 TON PER DAY BASIS)

		$FeCl_3$ Conditioning Costs 1966 Costs $	Freeze Conditioning Annual Estimated Costs $
1.	Acid House		
	Labor	38,000	28,000
	Unloading	8,000	4,000
	$FeCl_3$	775,000	230,000
	Maintenance	15,000	15,000
	Miscellaneous	13,000	10,000
2.	Machinery Bay		
	Operating Labor	79,000	79,000
	Supplies	1,000	1,000
	Power	35,000	9,000
	Miscellaneous	17,000	17,000
3.	Filter House		
	Operating Labor	85,000	85,000
	Supplies	2,000	2,000
	Maintenance and Repair	150,000	50,000
	Air	12,000	10,000
	Power	11,000	840,000
	Miscellaneous	12,000	
4.	Amortized Capital Costs*	650,000	5,376,000
5.	TOTAL	1,903,000	6,756,000
6.	Cost/Ton Solids	21.88	77.77

*Based on 20 year life, 3%

SECTION VI

ACKNOWLEDGMENTS

The support of the Milwaukee Sewerage Commission and its personnel is acknowledged with sincere thanks. Their cooperation and assistance were of considerable aid in facilitating the work performed. In particular, the interest and cooperation of Mr. R. Leary, Chief Engineer and General Manager, and Mr. L. Ernest, Project Director, are gratefully acknowledged.

This investigation was carried out by the Ecology Division cf Rex-Chainbelt, Inc. Mr. Anthony Geinopolos directed the work and is the author of this report. The bench-scale studies, analytical determinations, and statistical investigations were conducted by Mr. R. Wullschleger and his staff. Their efforts and diligence were essential to the collection and evaluation of the data presented. Their contribution is sincerely acknowledged.

The support of the project by the Environmental Protection Agency, formerly the Federal Water Quality Administration, and the willing assistance and helpful advice of Project Officer Dr. Joseph B. Farrell in the conduct of the project and in the presentation of this report is acknowledged with sincere thanks.

SECTION VII

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SECTION VIII

APPENDICES

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APPENDIX A

BELT FREEZING SYSTEM SPACE REQUIREMENTS

AND EQUIPMENT COST ESTIMATES

A. Design Basis

1. System to process 3 dry tons solids per day
2. Sludge to be thickened to 4% solids prior to freezing and dispensed onto the belt conveyor to a liquid depth of 1/2 inch
3. Sludge detention time on belt conveyor is 115 minutes (from bench scale tests)
   a. Sensible heat removal (60° F to 32° F) = 15 min
   b. Latent heat of fusion and sensible heat removal (32° F to 20° F) = 100 min
4. Conventional indirect refrigeration equipment to be used.
   a. Compressor
   b. Condenser
   c. Coolant chiller

B. Equipment Design and Costs

1. Refrigeration Equipment

Thickened Sludge Flow Rate, Q (lb wet/min)

$$Q = \frac{6{,}000 \text{ lb D.S.}}{\text{day}} \times \frac{\text{lb wet}}{0.04 \text{ dry}} \times \frac{\text{day}}{1{,}440 \text{ min}} = 104.1 \frac{\text{lb}}{\text{min}}$$

Weight of Sludge on Belt Conveyor, W (lb wet)

$$W = Q \times \text{detention time}$$

$$= 104.1 \frac{\text{lb}}{\text{min}} \times 115 \text{ min}$$

$$= 11{,}971 \text{ lb}$$

Tons of Refrigeration Required

1. Sensible Heat Removed

$$(60^\circ \text{ F} - 32^\circ \text{ F}) = 11{,}971 \text{ lb} \times \frac{\text{BTU}}{\text{lb-}^\circ\text{F}} \times 28^\circ \text{ F} \times \frac{1}{115 \text{ min}}$$

$$\times \frac{60 \text{ min}}{\text{hr}} \times \frac{\text{ton-hr}}{12{,}000 \text{ BTU}} = 14.55 \text{ tons}$$

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$$(32^{\circ}\ F - 20^{\circ}\ F) = 11{,}971\ lb \times \frac{0.5\ BTU}{lb\text{-}^{\circ}F} \times \frac{1}{115\ min}$$

$$\times \frac{60\ min}{hr} \times \frac{ton\text{-}hr}{12{,}000\ BTU} = 3.12\ tons$$

2. Latent Heat

$$11{,}971\ lb \times \frac{144\ BTU}{lb} \times \frac{1}{115\ min} \times \frac{60\ min}{hr}$$

$$\times \frac{ton\text{-}hr}{12{,}000\ BTU} = 74.94\ tons$$

3. Heat Losses
   Assume 20% of Items 1 and 2 = 18.52 tons

4. Total Tons Refrigeration Required
   Total Tons = 111.13

Refrigeration Power Requirements

Say, $\frac{2\ HP}{ton} \times 111.13\ tons = 222.26$ horsepower

Refrigeration Equipment Required

Integrated refrigeration equipment packages are commercially available which contain the required compressors, condensers, and coolant chiller tanks. The following information was obtained from Vilter Manufacturing Corporation, Milwaukee, Wisconsin (Bulletin No. 548).

1. Refrigeration power requirement = say, 225 HP
2. Use 2 - 100 HP units and 1 - 25 HP unit
3. Dimensions
   a. 100 HP unit - 147" l x 35.5" w x 86" h
   b. 25 HP unit - 140" l x 33" w x 73" h
4. Floor space requirements
   a. 100 HP unit (two required)

      $2 \times \frac{147 \times 35.5}{144} = 73$ sq ft

   b. 25 HP unit (one required)

      $\frac{140 \times 33}{144} = 32$ sq ft

   c. Total floor space = 105 sq ft
5. Refrigeration equipment costs (Vilter Mfg. Corp., Milwaukee, Wis.)
   a. Compressors = $15,500
   b. Coolant Chillers = $13,000
   c. Erection = $19,000
   d. Total = $47,500

2. Belt Conveyor Equipment

The steel belt conveyor assembly is comprised of,

a. Complete end assembly systems including two pulleys, drive, take-ups, tensioners, safety equipment, etc. at a cost of $8600 (1968 prices).
b. Mild carbon steel belting in standard 12 foot sections including brine coolant pans, piping, etc. at a cost of $2100 (1968 prices).
c. The maximum recommended belt width available is four feet. Items (a) and (b), above, reflect the costs associated with four foot wide mild carbon steel belt assemblies.

For a given application the belt freezing system may consist of (a) a single long belt assembly or (b) short, multiple belt assemblies "stacked" one on top of the other. Both options are considered in the following discussion.

a. Multiple Belt Conveyor Assemblies

Each conveyor in the multiple belt system would consist of a flexible steel belt with rubber sides bonded to the upper side to retain the sludge and rubber V-belts bonded to the underside to provide a means for driving the belt. The belt would float or ride in a coolant bath (see Figure 3b in text).

Assume the effective dimensions of each belt to be 48 in wide and 24 ft long and carrying 1/2 in depth of sludge. Then, the volume of sludge on each conveyor is,

$$\frac{48}{12} \times 24 \times 1/2 \times 1/12 = 4.0 \text{ cu ft}$$

and the effective weight of sludge on each conveyor will be,

$$4.0 \text{ cu ft} \times 62.4 \frac{\text{lb}}{\text{cu ft}} = 249.6 \text{ lb}$$

The total weight of sludge undergoing freezing on all conveyors in the system is 11,971 lb (see Item B.1, above). The number of conveyors required, therefore, is,

$$\frac{11,971}{249.6} = 48 \text{ conveyors}$$

The pulley diameters per belt, according to the manufacturer, Sandvik Steel, Inc., Skokie, Illinois, should be a minimum of 800 times the belt thickness. Assuming an available belt thickness of 0.032 in, the minimum pulley diameter is

$$800 \times 0.032 = 25.6 \text{ in}$$

The maximum height available at the Milwaukee Plant is 40 feet. Assuming the height of each conveyor is 4 feet, then the 48 conveyors may be erected in 6 tiers containing 8 conveyors per tier. Shown in Figure A-1 is the structure designed to contain 16 conveyors (one dry ton solids per day capacity) in 2 tiers. Three such structures would be required for the three ton solids per day pilot demonstration plant. The effective floor space requirements for the 3 ton solids per day plant are,

$$3 \times 34 \times 11 = 1{,}122 \text{ sq ft}$$

The material costs for the structures to contain the 48 belt conveyors (see Figure A-1, three required) are presented in Table A-1. The estimated erection cost for the structures required may be broken out of Table A-2.

The belt conveyor material costs, including pulleys, drives, take-ups, tensioners, safety equipment, belting, coolant tanks, piping, etc. are,

$$48 \times \$8{,}600 + 96 \times \$2{,}100 = \$614{,}400$$

The estimated erection cost for installing the belt conveyor equipment may be broken out of Table A-2.

Additional equipment required to round out the breezing system include conveyor sludge feeders, conveyor product ice-breakers, conveyor product ice unloaders and insulation. The equipment cost of these items is tabulated below.

Sludge feeders	$19,560
Ice breakers	$ 6,000
Unloaders	$13,600
Insulation (installed) (11,424 sq ft @ $7/sq ft)	$47,600

The cost of installing the feeders, breakers and unloaders may be broken out of Table A-2.

A summary of the freezer system capital costs, including erection, is shown in Table A-3. The total cost shown in Table A-3 is $883,900.

The effective floor space requirements for the multiple belt conveyor freezing system are approximated below.

Refrigeration equipment	= 105 sq ft
Belt conveyor system (3 x 11' x 34')	= 1,122 sq ft
TOTAL	= 1,227 sq ft

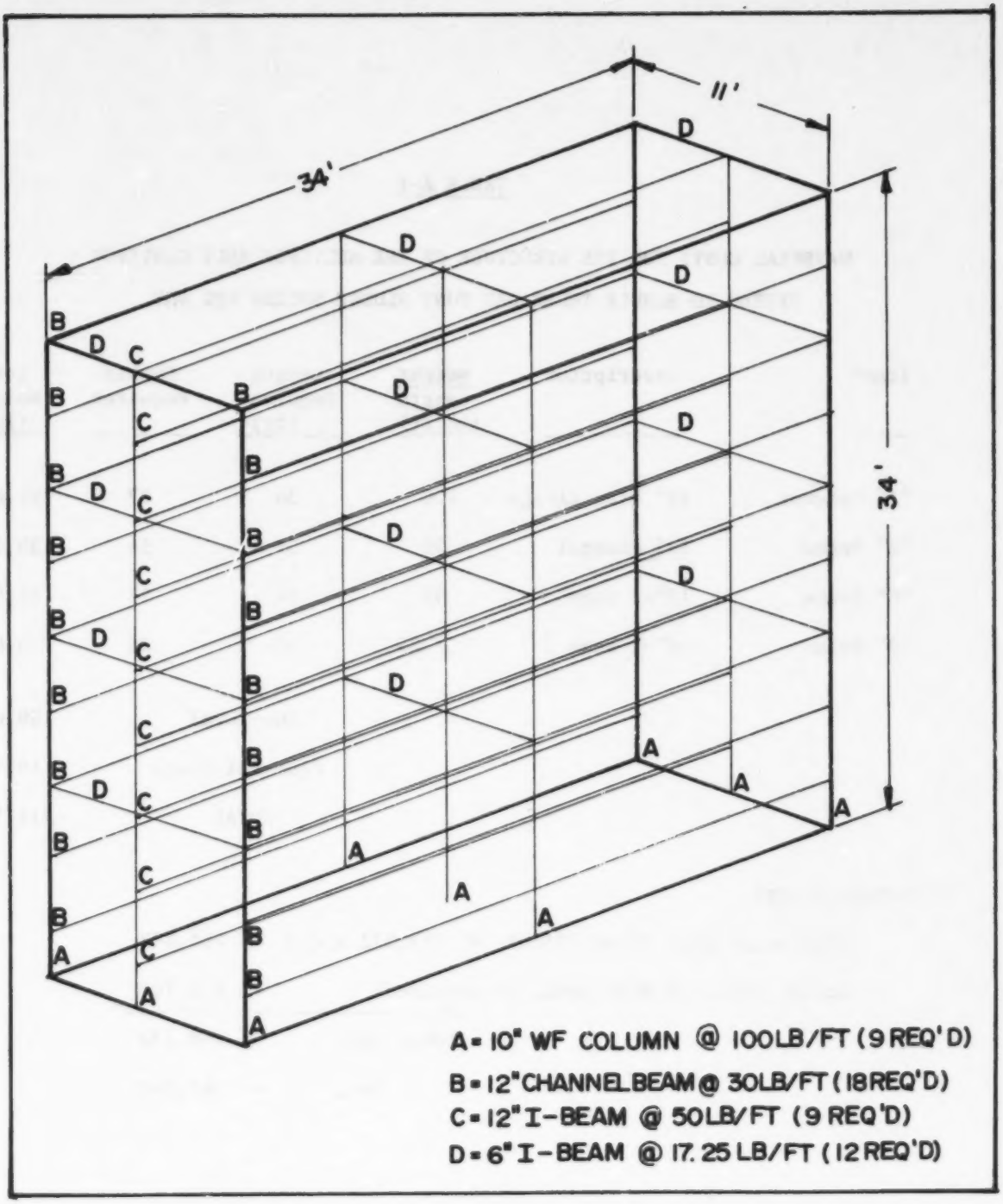

FIGURE A-1. BELT CONVEYOR STRUCTURE
1 TON SOLIDS/DAY CAPACITY

TABLE A-1

MATERIAL COSTS FOR THE STRUCTURE OF THE MULTIPLE BELT CONVEYOR SYSTEM TO HANDLE THREE DRY TONS SLUDGE SOLIDS PER DAY

Item*	Description	Weight Length (lb/ft)	Length Required (ft)	Number Required	Total Weight (lb)
"A" Columns	10" wide flange	100	34	27	91,800
"B" Beams	12" channel	30	34	54	55,080
"C" Beams	12"-I beam	50	34	27	45,900
"D" Beams	6"-I beam	17.25	11	36	6,831
				Sub-Total	199,611
				Plus 10% Misc.	19,961
				TOTAL	219,572

Material Cost

Fabricated Cost (@ $0.30/lb) = 219,572 x 0.3 = $65,872

Column Bases (@ $100 each, 27 required) = $ 2,700

TOTAL COST = $68,572

Say, = $69,000

*Refer to Figure A-1 for nomenclature

TABLE A-2

ESTIMATED ERECTION COSTS FOR THE MULTIPLE BELT CONVEYOR SYSTEM TO HANDLE THREE DRY TONS SLUDGE SOLIDS PER DAY

Item		Man Hours Required
1	Prepare column bases	54
2	Erect columns	108
3	Assemble beams and square structure	468
4	Install brine pans	1,536
5	Install head and tail pulleys	768
6	Install belts	384
7	Install drives	288
8	Piping of brine pans	288
9	Install weirs	132
10	Piping of conveyor feeders	132
11	Install conveyor unloaders	480
12	Install ice breakers	96
13	Crane operation	480
14	Moving material and machinery into building	720
15	Sub-Total	5,934
16	De-bugging (10% of above sub-total)	593
17	Total hours required	6,527
18	Labor cost (@ $8.50/hour)	$55,480
19	Erection machinery rental	10,800
20	Total Erection Cost	$66,280
	Say,	$66,300

TABLE A-3

SUMMARY OF MULTIPLE BELT CONVEYOR FREEZING SYSTEM

CAPITAL COSTS (3 DRY TON SOLIDS/DAY)

Item	Description	Cost ($)
1	Refrigeration Equipment (compressors, condensers, chillers, Erection)	47,500
2	Structure (Table A-1)	69,000
3	Belt Conveyors	614,400
4	Sludge Feeders	19,500
5	Ice Breakers	6,000
6	Unloaders	13,600
7	Insulation (installed)	47,600
8	Erection (Table A-2)	66,300
9	TOTAL	$883,900

b. Single Belt Conveyor Assembly

The single belt conveyor would have a length equivalent to the sum of the effective lengths of the conveyors comprising the multiple belt conveyor system described above, or

Length = 48 x 24 = 1,152 ft

The effective floor space requirements would be,

1,152 ft long x 4 ft wide = 4,608 sq ft

It is recognized that the single belt concept for this application may be impractical because of the inordinate length of the conveyor. However, this concept is presented for comparison purposes with the multiple belt concept previously described.

Equipment costs for the single belt conveyor were calculated in a manner similar to that used for the multiple belt conveyor assembly. A summary of the estimated freezer system capital costs, including erection, is shown in Table A-4. The total cost shown in Table A-4 is $551,500.

The effective floor space requirements for the single belt conveyor freezing system are approximated below.

Refrigeration equipment	= 105 sq ft
Belt conveyor system	= 4608 sq ft
TOTAL	= 4713 sq ft

TABLE A-4

SUMMARY OF SINGLE BELT CONVEYOR FREEZING SYSTEM

CAPITAL COSTS (3 DRY TON SOLIDS/DAY)

Item	Description	Cost ($)
1	Refrigeration Equipment (compressors, condensers, chillers, Erection)	47,500
2	Structure	69,000
3	Conveying Equipment	210,200
4	Sludge Feeder	6,500
5	Ice Breaker	2,000
6	Unloader	4,500
7	Insulation (installed)	145,500
8	Erection	66,300
9	TOTAL	$551,500

APPENDIX B

THAWING SYSTEM SPACE REQUIREMENTS

AND EQUIPMENT COSTS

A. Thawing Process Description

The frozen sludge obtained from the belt conveyor freezer system will be melted on a suitable thawing conveyor prior to further and final dewatering on a horizontal dewatering conveyor.

The frozen sludge sheet is to be broken into small shards, to increase the available surface area for heat exchange, and discharged to a thawing conveyor containing a coarse porous medium. The porous medium will allow the melted ice water to drain off and be utilized as a refrigeration condenser cooling source and/or heat exchanged with the incoming thickened feed sludge to the sludge freezing system.

The source of heat for melting the frozen sludge will be that recovered from the refrigeration system (heat of vaporization and heat of compression) and from auxiliary heat sources, as required. The thawing conveyor is to be insulated to minimize losses. Provision for washing the medium will be made.

B. Design Basis

1. The thawing conveyor will be capable of handling frozen sludge containing 3 dry ton solids per day.
2. Assume ice to be delivered to the thawing conveyor at about 5° F.
3. Frozen sludge to be completely thawed at discharge end.
4. Melted ice water to be collected and suitably disposed of.

C. Calculations

1. Heat requirements to thaw frozen sludge from 5° F to ice water at 32° F

   a. Ice production rate

   $$150{,}000 \frac{\text{lb ice}}{\text{day}} \times \frac{\text{day}}{24 \text{ hr}} = 6250 \text{ lb/hr}$$

   b. Sensible heat requirements to raise the temperature of the ice from 5° F to 32° F

   $6250 \times 0.5 \times 27 = 84{,}375$ BTU/hr

   c. Latent heat requirements

   $6250 \times 144 = 930{,}000$ BTU/hr

d. Total theoretical heat required = 1,014,375 BTU/hr

2. Surface area per unit weight of broken ice

a. Assume ice sheet is broken up into shards having the effective dimensions, 1/4" x 1/4" x 3/8"

Shard area = (2 x 1/4" x 1/4") + (4 x 1/4" x 3/8") = 0.5 sq in

Shard volume = 1/4" x 1/4" x 3/8" = $\frac{3}{128}$ cu in

b. Surface area per unit shard weight

$$\frac{0.5}{144} \times \frac{128}{3} \times \frac{1728}{62.4} = 4.1 \text{ sq ft/lb ice}$$

3. Rate of actual heat transfer required

a. Assume only 50% of apparent surface area (Item C2b, above) is available for effective heat transfer

$$0.5 \times 4.1 \frac{\text{sq ft}}{\text{lb ice}} = 2.05 \frac{\text{sq ft}}{\text{lb ice}}$$

b. Rate of actual heat transfer required

(1) Assume inlet air temperature of 150° F
(2) Assume exit air temperature of 70° F
(3) Assume straight line temperature drop, then average temperature is 110° F and average temperature drop is 110-32 = 78° F
(4) Overall heat transfer coefficient

From Chemical Engineers' Handbook, J. H. Perry, Ed., 3rd Edition, p. 481, Table 4, the overall heat transfer coefficient, U, for hot air blowing over and under a stainless steel conveyor, may vary from 5 to 7 BTU/(hr)(sq ft)(°F). A value of U of 5 BTU/(hr)(sq ft)(°F) is assumed for this application.

(5) Rate of actual heat transfer required

$q = UA\,dt$

where q = rate of heat transfer, BTU/hr
U = overall heat transfer coefficient, BTU/(hr)(sq ft)(°F)
A = heat transfer area, sq ft
dt = temperature difference, °F

$$q = 5 \times 2.1 \frac{\text{sq ft}}{\text{lb ice}} \times 6250 \text{ lb ice} \times 78 = 5{,}118{,}750 \text{ BTU/hr}$$

4. Thawing Conveyor Effective Area

a. It was observed in the laboratory that the bulk density of ice shards having individual effective dimensions, 1/4" x 1/4" x 3/8", is 23 lb/cu ft.

b. The bulk ice rate to be handled by the thawing conveyor is,

$$6250 \frac{lb}{hr} \times \frac{cu\ ft}{23\ lb} = 272 \text{ cu ft/hr}$$

c. Assuming the prototype conveyor has a detention time of one hour, the volume of ice on the conveyor at any time is 272 cu ft. Assuming a 4 ft wide conveyor having a bulk ice depth of 2 in, then the length of the conveyor is,

$$L = \frac{272 \times 12}{2 \times 4} = 408 \text{ feet long}$$

d. Effective floor area required

$$A = 408 \times 4 = 1632 \text{ sq ft}$$

5. Thawing Conveyor Equipment Costs

The major components comprising the thawing conveyor include the conveyor medium (40 x 60 mesh openings), drives, pulleys, take-ups, blowers, wash pump, ice water collection trough, and insulation. The estimated cost of the thawing conveying equipment, including erection but excluding site and housing is $65,000.

APPENDIX C

DEWATERING SYSTEM EQUIPMENT COSTS

AND SPACE REQUIREMENTS

1. Design Criteria

   a. Production Rate = 10 lb/(hr)(sq ft)
   b. Screen Loading = 0.15 lb/sq ft
   c. Detention Time = 1.0 min
   d. Vacuum = 5" Hg
   e. Provision for washing of media

2. Equipment Selection

   Suitable equipment was commercially available from various vendors. The dewatering equipment selected had the following salient features.

   a. Effective dimensions = 2'w x 12'l
   b. Variable belt speed = 2 to 12 fpm
   c. Variable vacuum levels, up to 22" Hg
   d. Continuous media washing
   e. Compartmentalized vacuum boxes capable of independent operation

3. Equipment Costs

a.	Horizontal filter belt structure, constructed with mild structural frame, type 304SS contact parts and segmented belt.....	$12,000
b.	Vacuum receiver.....	$ 850
c.	Vacuum pump.....	$ 2,700
d.	Filtrate pump.....	$ 725
e.	Erection.....	$ 500
f.	Total.....	$16,775
	Say,.....	$16,800

4. Space Requirements

   Effective floor space required = 2' x 12' = 24 sq ft

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APPENDIX D

CHEMICAL TREATMENT EQUIPMENT COSTS

AND SPACE REQUIREMENTS

1. **Design Basis**

   a. Chemical additive - Ferric Chloride
   b. Ferric chloride concentration = 20% $FeCl_3$
   c. Ferric chloride design dosage = 50 lb/ton

2. **Chemical Treatment Equipment Costs**

a.	Stock storage tank (215 gal)	$ 85
b.	Structure including erection	$ 250
c.	Storage tank mixer	$ 255
d.	Chemical feed pump	$ 500
e.	Total	$1,080
	Say,	$1,100

3. **Space Requirements**

   A = 4' x 4' = 16 sq ft

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